Residual Stress Fields
due to Static and Dynamic Indentation

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A: Description of Experiment:

Many problems in material mechanics have eluded full understanding due to an inability to characterize local strain fields with sufficient resolution. For crystalline materials, very high-resolution x-ray diffraction possible in a parallel beam geometry at a synchrotron source offers a solution as demonstrated by our preliminary work on beamline 2-1 as well as the work of others (see, for example [1,2]).

The characterization of stress fields surrounding a damage site caused by hard-body impacts is one example of a problem that can benefit greatly from highly-resolved x-ray diffraction. This problem is particularly relevant to the life prediction and failure prevention in aircraft turbine engines where the lifetime of components can be degraded by several orders of magnitude due to Foreign Object Damage (FOD). FOD, resulting from the ingestion of runway debris, birds, etc. has been shown to be a prime cause of High Cycle Fatigue (HCF) failure and is a major concern of the Air Force in terms of safety, maintenance costs, reliability, and readiness [3,4]. While several investigations are currently underway to characterize the influence of FOD on fatigue life, the damage distribution associated with the FOD impact has not yet been experimentally measured. It is this damage distribution which controls the initiation and early growth of fatigue cracks from FOD sites which lead to the eventual failure of the overall component. Proper characterization should provide critical mechanistic insight into the residual stress state and its influence on fatigue behavior.

We are proposing to map the residual strain distribution around damage sites caused by foreign object impacts using synchrotron x-ray diffraction and correlate the corresponding stress distribution to the driving force for initiation and early growth of "small" cracks under fatigue loading conditions. Both the change in peak position as correlated to a mean residual strain and the change in peak width correlated to a defect density will be probed using a relatively small probe size (~0.3 mm). The experimental results will be compared to (a) recent theoretical models of the spherical indent problem, e.g. via the finite element method (FEM), to verify the magnitude and dimensions over which these stresses are important and (b) fatigue experiments where cracks are initiated from sites of simulated foreign object damage.

While x-ray diffraction patterns can be obtained from sealed tube sources there are two reasons why a synchrotron x-ray source is essential for the proposed measurements of strain fields surrounding FOD impact sites. To measure the gradient in strain, it is necessary to measure small changes in strain associated with very small changes in the peak positions possible only with a high-resolution diffractometer using a low divergence source. Furthermore, to map out the distribution of strain it is necessary to have a sufficiently small probe size (~0.3 mm) which can only be achieved with an intense source.

The remainder of this proposal describes the x-ray experiment including a description of the calibration technique and preliminary results obtained on beamline 2-1 at SSRL, followed by a section on comparison of results to numerical modeling (via the finite element method) as well as fatigue crack initiation studies.

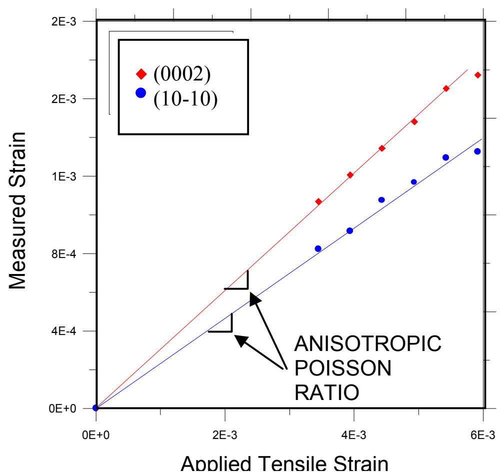
Proposed x-ray Measurements

The materials of interest consist of a Ti-6Al-4V alloy consisting of a bimodal distribution of primary-α (HCP) grains and lamellar colonies of alternating α and β (BCC) plates and a fine-grained Nickel alloy (FCC). The Ti-6Al-4V alloy is currently used in the front stage of turbine engines where the FOD problem is most significant. This same material is currently the focus of a joint industry-military-academia program to study the failure mechanisms associated with high cycle fatigue. While the microstructure (anisotropic and textured) is not ideally suited for precise x-ray diffraction based residual strain measurements, it does allow the capabilities of the analysis to be investigated. Alternately, the Nickel alloy can be used without loss of generality to provide increased resolution due to its simple crystallography (cubic) and absence of texture. Additionally, the refined grain size (~3 μm compared to ~20 μm for Ti-6Al-4V), will improve powder diffraction sampling statistics for the small spot sizes. In both materials, damage has been simulated using hardened steel spheres either by firing onto the surface at 200-300 m/s or by quasi-static indentation. The resulting impact craters are ~2-6 mm in diameter with the strain field expected to be appreciable over many millimeters.

Calibration of the strain measurement technique can be achieved by applying known strain levels to a standard. In preliminary work, a strain-gaged Ti-6Al-4V specimen was loaded in an in-situ straining rig to various levels of strain. Measurements of the surface-normal Poisson strain were then compared to the applied tensile strain via the appropriate elastic constant, Fig 1. A refined in-situ loading rig will be used in continued studies to both minimize extraneous non-tensile loading and provide known levels of plastic strain for determination of peak broadening due to the presence of dislocations. This calibration technique provides both a basis by which to verify the technique (by comparing to known elastic constants) as well as an estimate of the associated error of the technique.

The most important information to be gained from the residual strain measurements around sites of foreign object damage is (a) the magnitude of the residual radial and hoop stresses near the surface (most importantly, the location at which these stresses are maximum), and (b) the peak broadening near the indent as a possible measure of the degree of plastic damage. For both of these measurements, the spatial scale of interest is ~0.3 mm, thereby requiring an incident slit size of these dimensions or microfocusing optics. The relatively small spot size will also allow for measurements *in* the impact crater, when the overall curvature of the crater is considerably larger than the spot size, and the specimen is tilted such that the interrogated crater floor is properly oriented.

Preliminary studies utilized a relatively coarse 1 mm x 1 mm spot size in beamline 2-1 to measure the surface normal strain near the indent in the Ti-6Al-4V alloy. These studies stepped incrementally away from the FOD impact crater in 0.5 mm increments. For comparison to the unstrained condition, a region far away from the indent was also measured. The most interesting aspect of the results was the presence of regions of both tensile and compressive residual strain, Fig 2. While these findings are indeed quite interesting and immediately useful to the prediction of crack formation, a more thorough interrogation using a refined spot size ~0.3 mm is necessary to verify the location of the regions of tension and compression, as well as probe the crater floor.



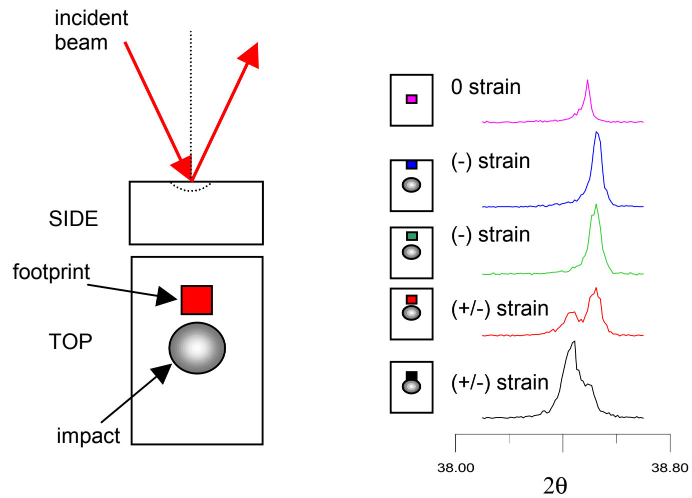


Fig 1. Calibration technique on Ti-6Al-4V. *Fig 2. (a) Configuration and (b) bifurcating (0002) Peak*

Initial sessions will focus on the Nickel alloy with relatively large indentations (~6 mm diameter), identifying only surface-normal Poisson strain (symmetric diffraction) in the near surface layer with minimal penetration depth (~5 µm). However, based on these results, later studies may utilize the continuously tunable source to examine the depth dependence of stress by varying penetration depth (see, for example [5]). More importantly, continued work will use asymmetric diffraction conditions to obtain the full stress tensor (see, for example [1,6]), although the Poisson strain alone should be sufficient to verify the FEM calculations.

The latter sessions will focus on the Ti-6Al-4V alloy by comparing simulated FOD damage to similarly sized damage created on turbine blades in-flight. Here, the aim will be to first investigate the capabilities of the technique in a non-ideal material by looking at the simulated high-velocity impact damage and comparing to the Nickel standard. Finally, an actual damage site on a blade taken out of service will be investigated as a means of correlating the residual stress state to both the numerical modeling and the simulated damage.

Comparison to Numerical Modeling and Fatigue Studies

Of particular importance in this study is to compare the results obtained by synchrotron x-ray measurments to that obtained by FEM simulation as well as the results of fatigue studies. FEM calculations are currently underway to simulate the axisymmetric problem of a hard spherical indenter on a Ti surface. In this modeling, parameters such as the coefficient of friction, and the influence of dynamic loading (as opposed to the typically simulated quasi-static case) are not well known. It is hoped that by coupling the 3-D FEM predictions with near-surface experimental x-ray measurements, a less ambiguous picture of the full 3-D stress state will arise. Indeed, recent results from the FEM calculations are consistent with the preliminary x-ray measurements: showing regions of both tensile and compressive stress on the surface, where the overall gradient exists over dimensions similar to the crater diameter [7].

Perhaps most importantly, the residual stress field from the simulated impact on Ti-6Al-4V will be compared to the fatigue behavior to determine the influence of these residual stresses on crack formation. As a first approximation, the residual stress is thought to merely superimpose on the mean stress of the fatigue cycle. The effect of a monotonic *applied* tensile stress superimposed on a given cyclic stress is well known to reduce both the initiation and growth life. It is believed, although remains to be verified, that the residual stress-induced mean load would have the same effect: initiation would occur most readily in the areas of highest residual tension (parallel to the loading axis). Experimental fatigue studies have been performed on the same material with FOD impacts simulated as described in the previous section for the x-ray measurements [8]. Interestingly, when the impact velocity is low (~200 m/s), cracks tend to form at the base of the indent; whereas, when the impact velocity is high (~300 m/s), cracks tend to form at the rim of the indent [9]. Specimens of these two velocities should provide a critical comparison of both the residual stresses and accumulated plastic damage at these two sites. From this information, a better understanding of the conditions that lead to crack formation will be developed. Furthermore, by comparing newly created damage to damage which has undergone subsequent fatigue cycling prior to crack initiation, this technique will allow us to characterize the relaxation of the stress field due to cyclic loading, a phenomenon which has received very little scientific attention.

Summary

The local residual stress fields caused by damage sites such as those formed by FOD have been attributed as a vital factor in component lifetime. While the work in this proposal focuses on the problem of foreign object damage with the end purpose of developing a better understanding of turbine engine failures, characterization of residual stress gradients around sites of damage is a more general problem, relevant to spherical hardness indentation, shot-peening, ballistics, etc. The synchrotron x-ray source is essential, enabling a highly resolved (in space and strain) experimental determination of these stress fields.

References

1. S. G. Malhotra, Z. U. Rek, S. M. Yalisove, and J. C. Bilello; *J. Appl. Phys.,* **79**, 6872 (1996).
2. A. Korsunsky, K. Wells, and P. Withers, *Scripta Mater.*, **39**, 1705 (1998)
3. J. M. Larsen, B. D. Worth, C. G. Annis, Jr., and F. K. Haake, *Int. J. Fract.*, **80**, 237 (1996).
4. B. A. Cowles, *Int. J. Fract.*, **80**, 147 (1996).
5. M. Harting; *Acta Mater.*, **46**, 1427 (1998).
6. M. Kobayashi, T. Matsui, and Y. Murakami, *Int. J. Fatigue*, **20**, 351 (1998).
7. J. W. Hutchinson and M. He, *private communication* (1999).
8. B. L. Boyce, J. P. Campbell, O. Roder, A. W. Thompson, W. W. Milligan, and R. O. Ritchie, *Int J. Fatigue*, in press (1999).
9. J. O. Peters, O. Roder, and R. O. Ritchie; *unpublished results* (1999).